

A Lab to Detect Radio Pulsars Using a Remotely Accessed 18-Meter Radiotelescope

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An undergraduate laboratory experiment where students use an 18-m radio telescope to observe radio pulsars is described. The telescope, which is located near the New Jersey shore town of Belmar, is accessible via the internet allowing students to acquire data remotely. The relatively weak pulsar signals are extracted from the background noise using signal averaging.

I. INTRODUCTION

A. Pulsars

Most stars have masses similar to that of the Sun and can be expected to burn “slowly” for a billion years or more. About one star in a hundred, however, is considerably more massive than the Sun (perhaps $10M_{\odot}$) and consumes its fuel at a much higher rate, arriving at a spectacular end in the form of a supernova explosion after about 10 million years. Most of the mass of the progenitor star is expelled into space, leaving behind a highly magnetized and rapidly rotating neutron star. Heavier progenitor stars ($M > 15M_{\odot}$) completely collapse, forming black holes.

Neutron stars are compact objects, having radii $R \simeq 10$ km and masses $M \simeq 1.4 M_{\odot}$. They are made of matter in which the protons and electrons of the progenitor star combine to form neutrons, which coalesce with existing neutrons to form what is essentially a giant nucleus. The density of the matter that comprises a neutron star is $\rho \simeq 2.3 \times 10^{17}$ kg/m³. One teaspoon of this material weighs about three billion tons.

Pulsars [1, 2] are highly magnetized rotating neutron stars that emit beamed broad-band electromagnetic radiation. The angular momentum of the progenitor star is retained, resulting in a rapid rotation rate due to the dramatic reduction in the moment of inertia. Most of the magnetic field of the progenitor star is trapped and intensified as the star collapses, resulting in surface fields on the order of $10^8 - 10^{12}$ T. The bulk of the neutron star may be considered superconducting, trapping the magnetic field.

The axis of the trapped magnetic field is typically not aligned with the rotation axis of the star resulting in a wrapping of the magnetic field lines around

the pulsar. Electrons trapped on the field lines are magnetically accelerated and emit curvature radiation. The high energy photons from the curvature radiation produce electron-positron pairs. The net effect is to produce bunched charged particles that emit narrow beams of intense radio frequency radiation[3, 4]. These beams sweep across the sky as the pulsar rotates and appear as pulses of radiation to observers in the beam’s path. The effect is akin to that of a steadily burning rotating lamp from a lighthouse that to distant observers appears to blink as the beam sweeps over them. The repetitive nature of this signal led to the discovery of the first pulsar by Jocelyn Bell Burnell and Anthony Hewish in 1968[5].

Pulsar periods range from 1.4 ms to 12 s. They have enormous moments of inertia and are relatively isolated, resulting in extremely stable rotation rates. In fact, for measurements on long time scales (years), some pulsars rival (but fall short of) the accuracy of atomic clocks[6]. Pulsars emit radiation over a wide range of frequencies, some even emit x -rays and γ -rays.

B. Signal Propagation and Detection

The pulsar signal passes through the interstellar medium (ISM) as it travels from the pulsar to our telescope. The ISM is a tenuous plasma through which different frequencies travel at slightly different speeds (dispersion). The density of the ISM along the line-of-sight to the pulsar is variable in both space and time. The resulting variations in the index of refraction mean that radiation will be slightly deflected as it propagates between the pulsar and the telescope. This causes the signal received at Earth to vary, analogous to the twinkling of stars caused by varying atmospheric density. This effect is termed *scintillation* and varies both with observa-

tion frequency and time, and can be strong enough that even a bright pulsar becomes temporarily unobservable at certain frequencies. Scintillation effects vary on multiple timescales ranging from seconds to weeks.

II. THE APPARATUS

The key piece of equipment is the 18 m parabolic antenna (TLM-18) shown in Fig. 1. This dish is located in Wall Township, a short distance from the New Jersey shore town of Belmar. It was originally used as a telemetry link to satellites and is most famous for having received the first weather images from space[7]. After lying fallow for several years, the dish has been re-purposed to serve radio-astronomy and amateur radio needs.

The TLM-18 antenna is attached to an altitude-over-azimuth mount. The telescope is equipped with 10 HP servo drives and position encoders on each axis, which are interfaced to a telescope control computer in the telescope operations building. The telescope can rotate 360° in azimuth and from 5° to 89° in altitude. Control software allows the dish to track objects as they move across the sky as a result of the Earth's rotation. The telescope can be controlled remotely using a network connection to the control computer.

A feed horn located at the focus of the parabola collects the radiation and couples it into a section of circular waveguide, where probes arranged at right angles are used to detect the horizontal and vertical components of the signal. A front-end receiver system at the feed point (see Fig. 2), amplifies and filters the signals so that they can be sent over coaxial cables to a nearby operations building, where the signals are digitized using a B210 Universal Software Radio Peripheral Module (USRP)[8] from Ettus Research before being processed and recorded by a software defined radio (SDR). The B210 USRP is outfitted with a GPS receiver, which controls the clock at the 50 ppb level and permits precise time stamping of the data. The SDR is based on GNUradio, an open-source set of modules widely used in the educational community[9].

The system can operate in the $1.0 < f < 2.0$ GHz range, with most observations being made in a 25 MHz band centered on 1420 MHz, the frequency corresponding to the 21-cm radio astronomy band. The diffraction limited beam size of the telescope is $\approx 1.0^\circ$ FWHM at this frequency.



FIG. 1: Site view of the TLM-18 telescope and the operations building. The feed horn and receiver are located at the focus of the primary mirror and held by four support struts. The operations building is in the background. The scaffold tower is used to provide access to the feed point for maintenance.

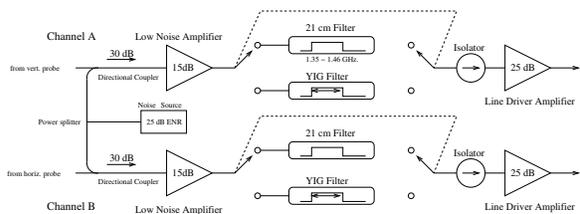


FIG. 2: Block diagram of the 21 cm receiver located at the feed point of the telescope. The two inputs on the left receive the signals from the coaxial couplers for the vertical and horizontal polarization. The two outputs on the right are connected to $\approx 200'$ coaxial cables that run from the feed point into the operations building. Each receiver channel can use either a fixed filter centered on the hydrogen 21 cm line, or a tuneable YIG filter. The noise source allows injection of an ≈ 50 K signal into the receivers inputs to serve as a calibrator.

III. LAB PROCEDURE

A. Planning

The dish is capable of observing several different pulsars. To see them, students need to know when and where to point the dish. This, in turn, requires knowledge of the various coordinate systems used in astronomy. In particular, students should learn what horizontal and equatorial coordinates are and what is meant by right ascension and declination. An extensive catalog of pulsars is published on the web by the Australian National Telescope Fa-

cility (ATNF)[10]. Students use this catalog to select targets that offer large flux densities and are likely to be well above the horizon during their lab period. Other desirable attributes include periods larger than 200 ms and reasonable duty factors (pulse widths). A simple Python script is provided to allow students to predict when a given pulsar will be in view.

B. Signal Acquisition and Processing

Even with a comparatively large antenna, individual pulses from a pulsar are too weak to be observed. Students are thus obliged to use signal averaging techniques to tease a signal out of the noise.

A special purpose receiver, implemented using `GNUradio` modules, subjects the incoming samples, which arrive at a rate of 25 MHz (40 ns between samples), to 32-channel fast Fourier transforms (FFTs) (40 ns \times 32 channels = 1.28 μ s per FFT). Since the data rate is too high to write directly to disk, the FFTs are averaged in blocks of 512 (1.28 μ s \times 512 = 0.64 ms per spectrum). The two streams of 32-channel spectra that result are written to disk at a rate of 1.5 kHz, where they await subsequent analysis[11].

Each spectrum comprises 32 four-byte floating-point numbers, resulting in an aggregate rate for both channels of $32 \times 4 \times 1.5 \times 10^3 \times 2 = 0.39$ MBytes/s = 1.4 GBytes/hr. A first data reduction step, in which the 32 values in each spectrum are combined into a single value, substantially reduces the size of the dataset. Each such sample is paired with a time stamp, expressed in terms of Modified Julian Date (MJD). The program used for this first data-reduction step produces files that can be read by either MATLAB or Python. The resulting datasets are about 50 MByte in size and are readily transferred over the internet. Students generally prefer to copy the data to their personal computers for offline analysis.

C. Offline Analysis

If the rotational period, T , of the pulsar is known, the time values can be converted to values of the pulsar's rotation phase, ϕ , which is typically expressed

as

$$\phi_i = \frac{\text{mod}(t_i, T)}{T} \quad (1)$$

where t_i is the time of the i^{th} sample. The power samples are then binned according to their ϕ values. The pulsar signal appears as a peak in the resulting histogram.

If the assumed rotation period is incorrect, the pulsar signal will be spread over many bins and will appear weaker and broader, and may even be completely washed out. Although the period value found in the ATNF catalog is a good initial guess, the period of a pulsar seen by an observer on Earth is affected by the Earth's rotation and the Earth's orbital motion around the Sun. The Doppler shift resulting from these motions is large enough to broaden the observed phase peak.

There are two ways to take this into account. The first is to vary the period T about the nominal value from the ATNF catalog, determining the best period by trial and error. This is the approach followed by most students. The second involves the use of a program called TEMPO[12], which provides a set of coefficients that can be used to calculate the absolute phase of the signal, given the target pulsar and the time and location of the observation.

The result from a typical student data set is shown in Fig. 3. The observed period of (0.714550 ± 0.000010) s differs from the ATNF value of 0.715520 s by 40 ppm, which is consistent with the expected Doppler shift from the Earth's orbital motion around the Sun. The baseline temperature, which comes mainly from receiver noise, is 99.5 K. The 600 mK peak signal from the pulsar is about 165 times smaller than the noise.

IV. OTHER MEASUREMENTS

The TLM-18 system has been used by numerous student groups for a variety of radio astronomy projects. Although smaller antennas are adequate for most studies of the 21 cm radiation from the Milky Way, the higher gain and narrower beam profile of the TLM-18 allow one to observe the hydrogen line from other galaxies (M31 and M33) and to make high resolution maps of the Milky Way. The antenna has also been used to observe circumstellar OH masers, which produce a distinct line at 1685 MHz.

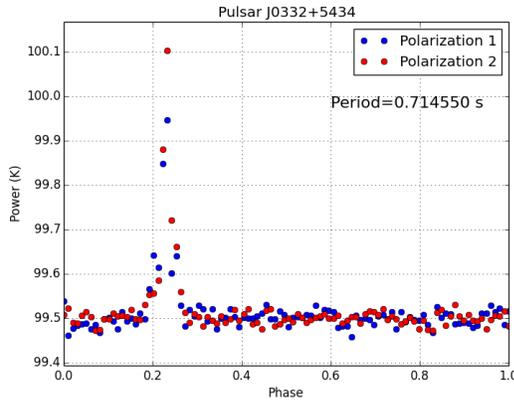


FIG. 3: Result from a typical student data set. The total integration time was 15.4 minutes, corresponding to about 1300 pulsar periods.

We are currently in the process of upgrading the TLM-18 with a wide band digitizer. This device will afford a ten-fold increase in bandwidth (from 2×25 MHz to 2×250 MHz), which will increase the number of pulsars that can be reliably detected. The wider bandwidth will also make it possible to observe the dependence of pulse arrival time on frequency, which in turn will allow a determination of the dispersion measure (and therefore distance) for selected pulsars.

Despite its capabilities, the TLM-18 sits idle for much of the time. We are therefore open to exploring arrangements for users from other institutions to take advantage of this valuable resource. Interested parties should contact the author at marlow@princeton.edu.

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 - [7] From the TIROS I weather satellite. See URL: https://web.archive.org/web/20120614035813/http://www.campevans.org/_CE/html/tiros1-2.html
 - [8] Ettus B210 <https://www.ettus.com/product/details/UB210-KIT>
 - [9] GNUradio web site URL: <https://www.gnuradio.org/>.
 - [10] Australia Telescope National Facility Pulsar Catalog. <http://www.atnf.csiro.au/people/pulsar/psrcat/>
 - [11] GNUradio is relatively easy to use. Students could, in principle, develop their own SDR modules. Learning to do so, however, would require more time than is typically available for junior-level lab experiments.
 - [12] URL: <http://tempo.sourceforge.net/>